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(54) Piezoelectric audio device and method for sound production

(57) An arrangement (1) to improve the sound quality of a piezoelectric element actuating element (AE). A sensing element (ME) is attached to the piezoelectric element to supply an electric response to movement of the element when the plate vibrates producing a sound. The response is electrically filtered in order to compensate said mechanical resonance frequency band for stabilisation of said first signal. The filtered response is inverting summed by a summation node (SN) with the audio signal to be reproduced in order to compensate the otherwise exaggerated amplitude at these resonance frequencies.

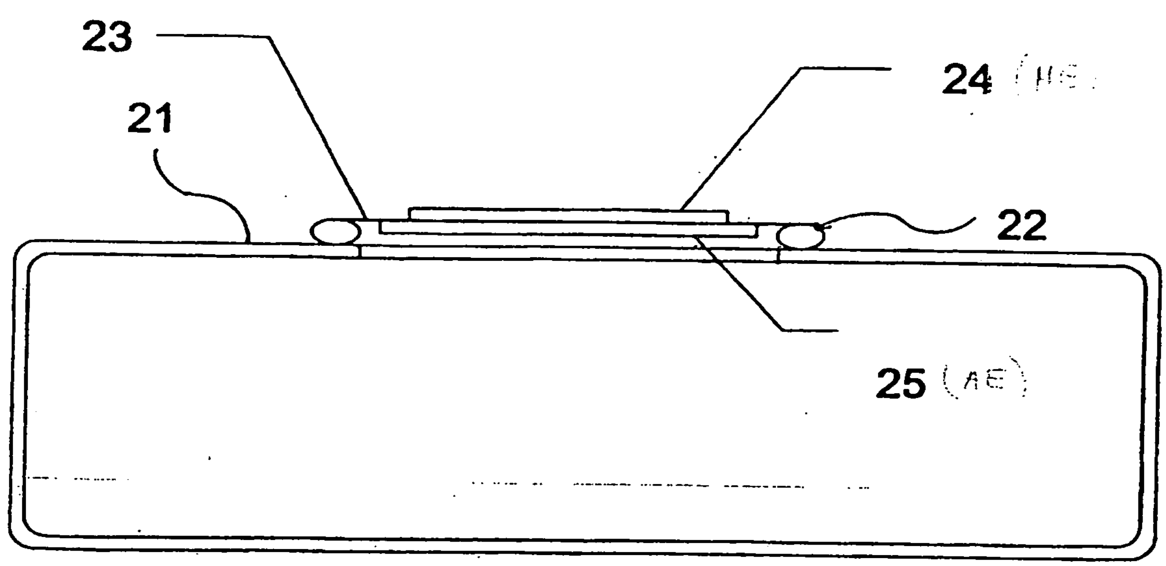

Fig. 2

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EP 1 051 058 A2

Description

[0001] The invention relates to piezoelectric loudspeakers, and moreover to mobile phones, telephones and ultrasonic devices having a piezoelectric element for sound production.

[0002] An earpiece or loudspeaker can be realised with several operating principles including electrodynamic, electromagnetic, electrostatic and piezoelectric operation. Piezoelectric transducers are also often called ceramic transducers. The most common operating principle at present is electrodynamic one, thanks to a good frequency response, small tendency to distortion and wide range of amplitude of sound that it provides. Despite these advantages there are situations where piezoelectric elements are appealing, especially when the device should be cheap, have low power consumption and they are small in size and weight. The performance of piezoelectric elements is, however, usually well below the quality expectations; they are plagued by both strong coloration and disturbing non-linearity of frequency response, and the maximum movement of the surface is much smaller in them than in the more common speakers leading to limited volume they can provide.

[0003] To overcome these problems there have been serious attempts to improve the frequency response of piezoelectric elements to utilise them for their good properties. While piezoelectric elements are small, cheap and require low input power, they have one or more individual resonance frequency bands, where their output is significantly amplified by the resonance. Most of the inventions to improve the frequency response of piezoelements are such as mechanical dampening pads. There is a patent application WO86/01362 where a portion of the surface of a piezoelement is used to give an electric feedback to the amplifier driving the piezoelement to control the gain of the amplifier. With such an arrangement it is possible to adjust the output power of a piezoelement in order to adjust the volume to a correct level. This solution is feasible to linearise the volume produced by a piezoelement when the sound consists of a single tone with a very narrow bandwidth. However, the solution is inappropriate to linearise the frequency response of a more complex sound, such as human voice or a sound of a musical instrument, because the volume amplification changes for the entire frequency band thus maintaining the colorisation caused by the piezo element. Besides, controlling of the gain on basis of a narrow frequency band could easily lead into instability, i.e. the piezo element could start causing loud noise in an uncontrolled state. US 4,451,710 discloses an electrical to acoustic transducer utilising a piezoelectric element. There a problem of variable sensitivity - i.e. sensitivity as a function of temperature, age and manufacturing process. By use of the voltage produced at the sense-element to modify the voltage applied to a drive element it is possible to nullify the dependence of the transducer sensitivity on the piezoelectric sensitivity of the foil. Thus this solution is substantially alike the one of WO 86/01362, and has the same drawbacks of colorisation of voice or sound of music instrument produced with a piezoelectric element.

[0004] Now a new arrangement has been invented where a piezoelectric sensor is mechanically attached to a sound producing piezoelement i.e. actuator for providing a negative feedback signal corresponding to vibration of the actuator. The actuator is fed by a sound signal generated by a piezoelement driver. The feedback signal is electrically filtered to compensate a mechanical resonance frequency band of the actuator for stabilisation of the feedback loop, and led with an incoming audio signal to the piezoelement driver in order to stabilise the sound signal. The electrical filtering for stabilisation may be implemented by means of frequency selective amplification, frequency selective phase transformation or a combination of those and the objective of the filtering is decreasing the amplitude of sound signal at th resonance frequency band to compensate enhanced gain of the actuator at its resonance frequency.

[0005] According to a first aspect of the invention there is provided a method for sound production, comprising:

inputting a first electric signal to a piezoelectric plate;
generating a second electric signal substantially proportional to movement of said plate, characterised in:
electrically filtering said second signal to compensate a mechanical resonance frequency band of said piezoelectric plate for stabilisation of an output signal;
receiving an electric audio signal;
subtracting said filtered electric signal from said electric audio signal to produce said output signal; and
outputting said output signal to said piezoelectric plate to generate with the piezoelectric plate an acoustic audio signal corresponding to said electric audio signal.

[0006] According to a second aspect of the invention there is provided a piezoelectric acoustic transducer comprising:

a piezoelectric plate having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element attached to said plat , said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, characterised in said transducer comprising:
an electric filter for generating a filtered signal from said second electric signal in order to compensate said

mechanical resonance frequency band for stabilisation of said first signal;
a summing means having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

The transducer preferably comprises an amplifier to amplify the sound signal prior to its feeding to the actuator.

[0007] According to a third aspect of the invention there is provided an earpiece comprising:

a piezoelectric plate having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, characterised in said earpiece comprising:
an electric filter for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;
a summing means having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

The earpiece preferably comprises an amplifier to amplify the sound signal prior to feeding it to the piezoelement.

[0008] According to a fourth aspect of the invention there is provided a telecommunication device comprising:

a piezoelectric plate having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, characterised in said telecommunication device comprising:
an electric filter for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;
a summing means having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

The telecommunication device preferably comprises an amplifier to amplify the sound signal prior to its feeding to the pi zoelement.

[0009] According to a fifth aspect of the invention there is provided an ultrasonic device comprising:

a piezoelectric plate having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, characterised in said ultrasonic device comprising:

an electric filter for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;
a summing means having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

[0010] The ultrasonic device preferably comprises an amplifier to amplify the sound signal prior to its feeding to the piezoelement.
[0011] The invention will be discussed below in detail by referring to the enclosed drawings, in which

Figure 1 shows a block diagram of a feedback piezoelectric transducer according to an embodiment of the invention;
Figure 2 shows a construction of a speaker arrangement according to an embodiment of the invention;
Figure 3 shows a block diagram of the measurement set-up used to test the speaker shown in Figure 2;
Figure 4 shows an impulse response of the sensor of the arrangement of Figure 2 with negative feedback (solid line) and without negative feedback (dashed line) according to the invention; and
Figure 5 shows a frequency response both with a system with feedback (smoother curve) and without feedback (higher peak).

[0012] A typical piezoelectric speaker comprises a thin circular (or rectangular) piezoelectric disk glued to a plate (typically metal). The plate is used as one electrode, and the other electrode is deposited on the other surface of the piezoelectric disk. Usually the electrode is printed using silver paint, which forms a conductive surface when the piezoelectric material is heated for creating the polarisation. The disk is polarised so that an electric field between the electrodes will create a radial stress. As this radial stress acts across only one surface of the plate, it causes blending of the plate.
[0013] The piezoelectric conversion from electric field to stress inside the material is relatively linear, and the nonlinearity associated with this conversion is of third order. The conversion from a radial stress i.e. force to a displacement of the plate can exhibit significant non-linearity, and can exhibit considerable asymmetry.
[0014] As the piezoelectric speaker relies on bending of a rather stiff plate, the achievable displacements will remain small, and improving linearity by improvements in the mechanical design is bound to have only limited success. Besides the non-linearity, another typical problem of piezoelectric speakers is irregularity of the frequency response. This arises from various resonance modes of the system. The axial modes (which can be problematic) can be controlled by mounting the driver suitably, but the lowest radial mode (actually a mass-spring-type resonance) cannot be controlled mechanically without a significant simultaneous loss of sensitivity.
[0015] Figure 1 shows a block diagram of a feedback piezoelectric transducer according to an embodiment of the invention. The transducer comprises an actuating element AE and a sensing element. The mathematics of the dynamics of the feedback system itself is exceedingly simple, if the various parts of the system are treated as black boxes. The feedback system can be described at simplest as an inverting summation amplifier SN with a finite-gain amplifier, with the amplifier transfer function consisting of the transfer function A_1 of the driving amplifier A1, the transducer (speaker i.e. actuator A2 and sensor A3 have transfer functions A_2 and A_3), and the sensing amplifier A4 with a compensating network (transfer function A_4). In addition to this we have the transfer function from the speaker driving voltage to the acoustical response ($A_{ma} = p_{out}/V_{spkr}$), wherein A_{ma} is the transfer function for acoustic power derived from the speakers input voltage i.e. speaker driving voltage. All these transfer function coefficients can be frequency-dependent and complex.
[0016] The transfer function of loop of such a circuit can be described by:

$$A_{tot} = -\frac{1}{1+\frac{1}{A_1 A_2 A_3 A_4}} \qquad (1)$$

where th total transfer function is calculated at the output of A_4 (or at the negative input of the summation node).

[0017] Thus, the voltage at the actuator driving point P1 is

$$V_{spkr} = -V_{in}\frac{1}{1+\frac{1}{A_1A_2A_3A_4}}\frac{1}{A_2A_3A_4} \qquad (2)$$

[0018] From this, the output sound pressure can be written as

$$p_{spkr} = -V_{in}\frac{1}{1+\frac{1}{A_1A_2A_3A_4}}\frac{A_{ma}}{A_2A_3A_4} \qquad (3)$$

[0019] When the electrical-mechanical and electrical-acoustical transfer functions have been determined, either experimentally or by a numerical model, the equations above enable design of the suitable equalisation.

[0020] The invention is next illustrated by describing one experiment system made.

[0021] As the output impedance of the piezoelectric sensor is high and almost purely capasitive, the input impedance of the sense amplifier determines both the sensitivity and the bandwidth of the device. Depending on the sensor structure, its capacitance varies from around 10 pF to 1 nF. At low frequencies this implies very high impedancies (e.g. 100 pF at 20 Hz implies about 77 Mohm). However, as it is impractical to apply piezoelectric loudspeakers (or headphones) at the very lowest frequencies, the lower limiting frequency can be chosen to be one order of magnitude higher, which implies that amplifier input impedance of around 1 - 10 Mohm II 10 - 20 pF is in practice sufficient. This estimate is also supported by measurement results, and such an input impedance is easily realisable. During the experiments it actually became apparent that it is beneficial to limit the low-frequency bandwidth of the signal conducted to the input of the sense amplifier already with the input impedance. The aforementioned limited movement of a piezoelement restricts the low-frequency response. The limitation is dependent on the size, mechanical and electrical properties of the element, and distance from the element to the observer. In headphone or headset use the practical frequency band can be extended to lower frequencies around 100 Hz ... 200 Hz. For a larger speaker, which is listened over longer distance, the respective limit may be at much higher frequency.

[0022] The measurements described below were carried out by using a speaker consisting of two separate piezoelectric transducers 24,25. Sensing transducer i.e. sensor 24 was glued on backing plate 23 of actuating transducer i.e. actuator 25. The transducers were attached to a 0.4 litre size sealed enclosure 21, which was filled with absorbing material. (The enclosure volume is of little consequence with piezo speakers, due to their stiff structure and thus very small equivalent volume, and of even less importance when feedback is used, but the size was chosen so that the diffraction effects in the acoustical measurements could be somehow reduced.) The edge of the transducer was attached to the enclosure with viscoelastic material 22. The viscoelastic lossy edge had a significant damping effect on the radial modes of the transducer.

[0023] For simplicity, the experimental set-up system 20 was realised with two separate transducers, actuator 25, and sensor 24. In commercial realisations cost reduction can be achieved by utilising the possibility of separating a fraction of the electrode area to act as a sensor. There are commercial products (buzzers for positive feedback having three connections) available, where the piezoelectric material is sandwiched between two electrodes and on either side another one of the electrodes is further divided in two mutually isolated parts. In this kind of structure, however, the stray capacitance between the actuator and sensor electrodes can limit the usable amount of feedback at high frequencies. Similar structures have already been used in other applications: in piezoelectric buzzers to provide positive feedback, which enables the buzzer to ring at the mechanical resonance frequency, thus improving efficiency, and in ultrasonic imaging, where separate transmitter and receiver areas are used to prevent the transmit pulse from overloading the receiving amplifier.

[0024] Figure 3 shows a block diagram of the measured set-up 30 used to test the speaker shown in Figure 2. To keep the experimental arrangement as simple as possible, small mixing console 32 was used as the summing amplifier, since it allowed easy gain adjustment and equalisation of both the input and feedback signal paths. A conventional laboratory measuring amplifier 36 was used as the input amplifier for sensor 24. The tone controls of the mixing console

were used to boost frequencies from 1 kHz upwards, and the maximum boost (about 12 dB) was achi ved at 10 kHz and above. The mechanic connection between actuating transducer 25 and sensor 24 is illustrated with connection 34. It is well known in the art, that frequency selective analogue signal processing may cause phase shifting to a signal and thus there are alternative ways in carrying out the selective boost of the signal. Considering th demand to enhance the subtracting effect of a response signal to the audio input, one can adjust the amplitude over the spectrum while keeping the phase shift constant over the whole range of spectrum, or one can adjust the shift while keeping the amplitude constant. Or, alternatively, both of these can be adjusted at the same time. The objective of the negative feedback is to improve the frequency response of a piezoelectric actuator and the electric filtering can be used to stabilise the dynamics of the control loop.

[0025] Figure 4 shows an impulse response of the sensor of the arrangement of Figure 2 with negative feedback (solid line) and without negative feedback (dashed line) according to the invention. The negative feedback shortens the time of dampening the impulse.

[0026] Figure 5 shows a frequency response both with a system with feedback and without feedback. The reference level of the amplitude scale is arbitrary. The curve with feedback is approximately 7 dB smaller in amplitude at frequency of 6 kHz. Using the invention the resonance peak is transferred from less than 6 kHz to approximately 10 kHz and the peak was also smoothed to have lower gradients around the maximum amplitude (the resonance bandwidth approx. 2 kHz without and 10 kHz with feedback) thus enabling a significant enhancement in the quality of sound reproduction. The measurement indicates that the feedback is effective for controlling the radial modes, but the axial modes, which create irregularities at 1 and 2 kHz are practically unaffected.

[0027] A piezoelectric element according to the invention can be used in earpieces of telephones, mobile telephones, wired telephones, wireless telephones, earpieces of portable cassette, CD- and DVD-players. While the invention is most appropriate in lightweight and portable devices, it is well suitable also to fixed mounted devices such as sonars etc.

[0028] This paper presents the implementation and embodiments of the invention with the help of examples. It is obvious to a person skilled in the art, that the invention is not restricted to details of the embodiments presented above, and that the invention can be implemented in another embodiment without deviating from the characteristics of the invention. Thus, the presented embodiments should be considered illustrative, but not restricting. Hence, the possibilities of implementing and using the invention are only restricted by the enclosed patent claims. Consequently, the various options of implementing the invention as determined by the claims, including the equivalent implementations, also belong to the scope of the present invention.

Claims

1. A method for sound production, comprising:

inputting a first electric signal to a piezoelectric plate;
generating a second electric signal substantially proportional to movement of said plate, **characterised** in:
electrically filtering said second signal to compensate a mechanical resonance frequency band of said piezoelectric plate for stabilisation of an output signal;
receiving an electric audio signal;
subtracting said filtered electric signal from said electric audio signal to produce said output signal; and
outputting said output signal to said piezoelectric plate to generate with the piezoelectric plate an acoustic audio signal corresponding to said electric audio signal.

2. A method according to claim 1, wherein

said filtering comprises one of the following: frequency selective amplification, frequency selective phase transformation and a combination of those.

3. A piezoelectric acoustic transducer (1) comprising:

a piezoelectric plate (25) having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element (24) attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, **charact rised** in said transducer comprising:
an electric filter (A4,32) for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;

a summing means (SN,32) having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

4. A piezoelectric acoustic transducer (1) according to claim 3, wherein

said electric filter (A4,32) has decreasing means for decreasing the amplitude of sound signal at the resonance frequency band to compensate enhanced gain of said piezoelectric plate (25) at its resonance frequency, said decreasing means comprising at least one of the following: means for frequency selective amplification, means for frequency selective phase transformation, and a combination of those.

5. An earpiece comprising:

a piezoelectric plate (25) having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element (24) attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, **characterised** in said earpiece comprising:
an electric filter (A4,32) for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;
a summing means (SN,32) having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

6. A telecommunication device comprising:

a piezoelectric plate (25) having a first input for inputting of a first electric signal, said piezoelectric plate having at least one mechanical resonance frequency band;
a sensing element (24) attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, **characterised** in said telecommunication device comprising:
an electric filter (A4,32) for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;
a summing means (SN,32) having:

a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
a second input for receiving said filtered electric signal;
means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

7. An ultrasonic device comprising:

a piezoelectric plate (25) having a first input for inputting of a first electric signal, said piezoelectric plate having

at least one mechanical resonance frequency band;

a sensing element (24) attached to said plate, said sensing element having a first output for outputting of a second electric signal substantially proportional to movement of said plate, **characterised** in said ultrasonic device comprising:

an electric filter (A4,32) for generating a filtered signal from said second electric signal in order to compensate said mechanical resonance frequency band for stabilisation of said first signal;

a summing means (SN,32) having:

> a first input for receiving a third electric signal comprising an electric audio signal to be reproduced acoustically by said piezoelectric plate;
>
> a second input for receiving said filtered electric signal;
>
> means for subtracting said filtered electric signal from said third electric signal to produce said first electric signal; and
>
> an output functionally connected to said first input to generate by the piezoelectric plate an acoustic audio signal corresponding to said electronic audio signal.

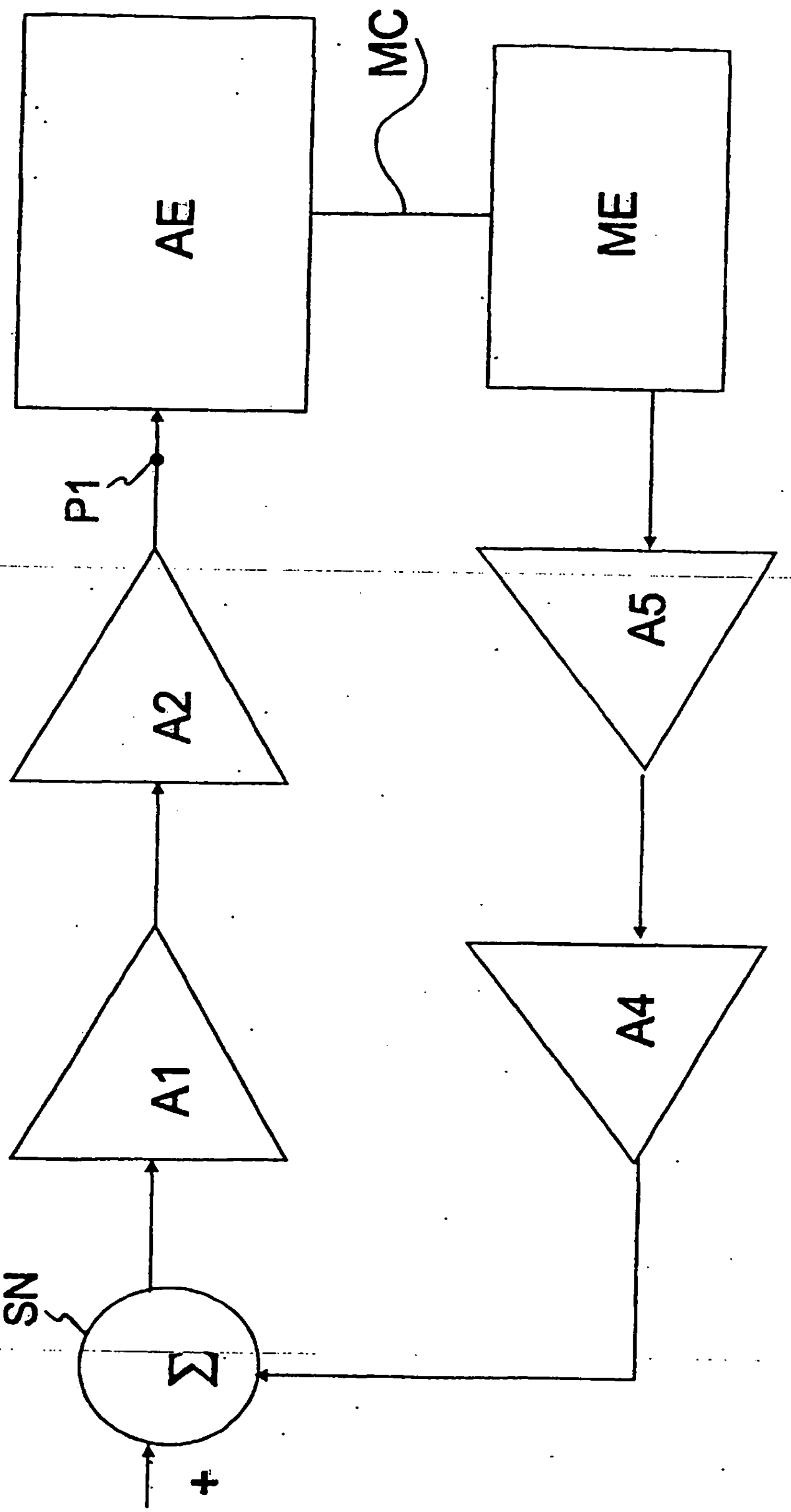

Fig. 1

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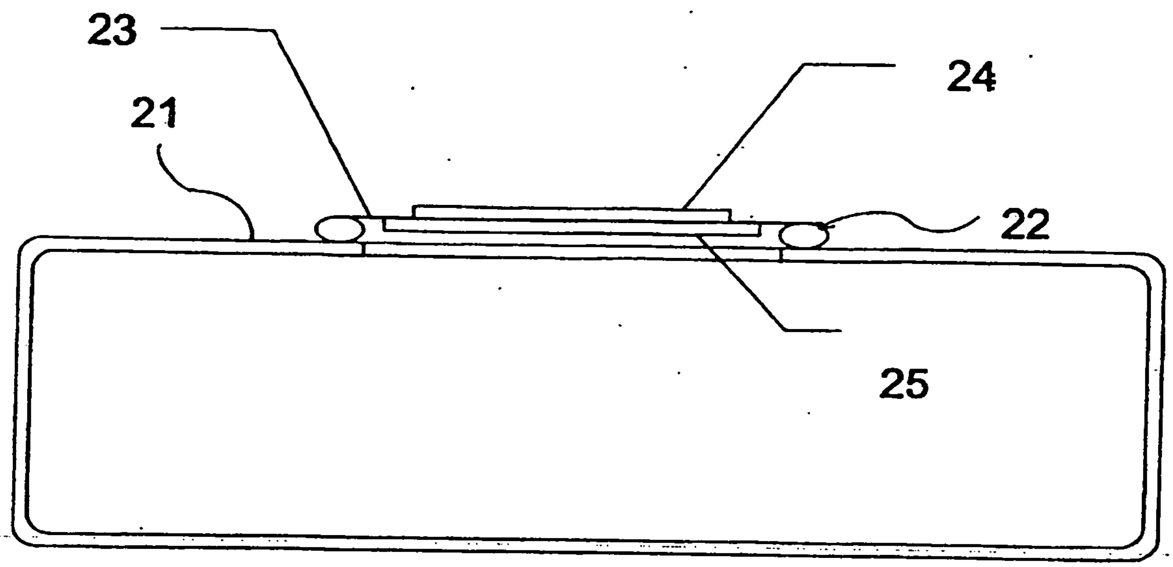

Fig. 2

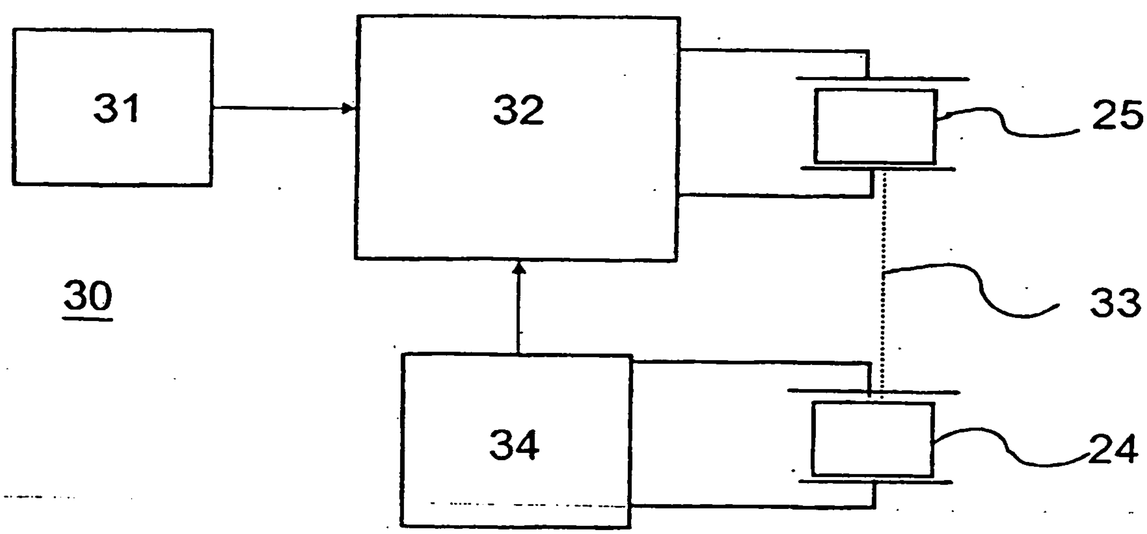

Fig. 3

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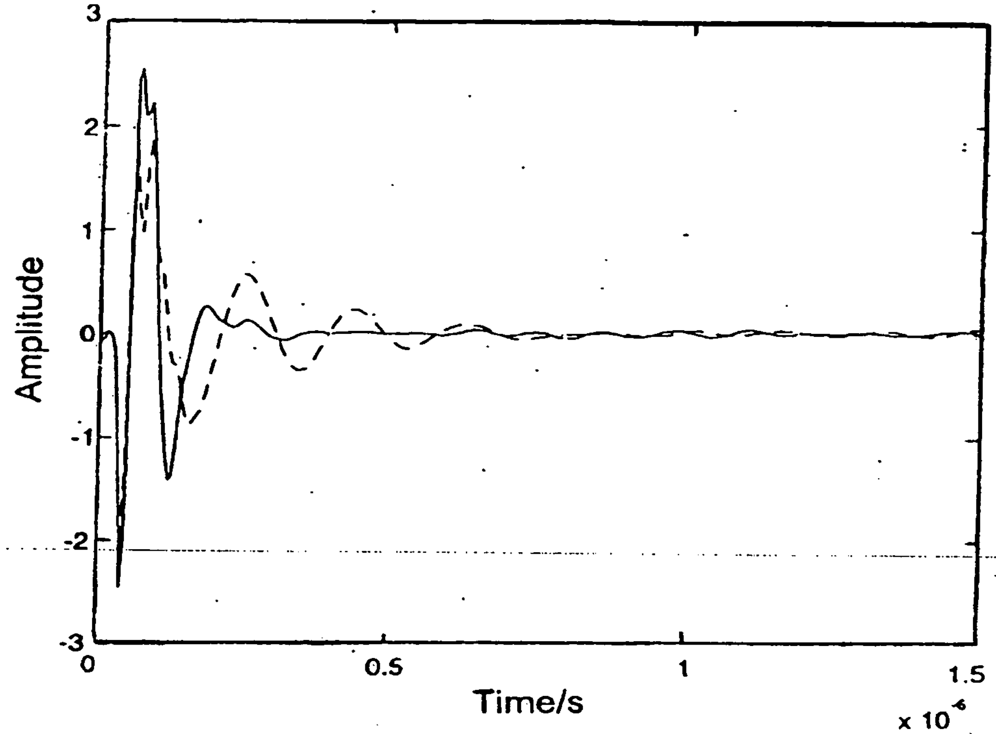

Fig. 4

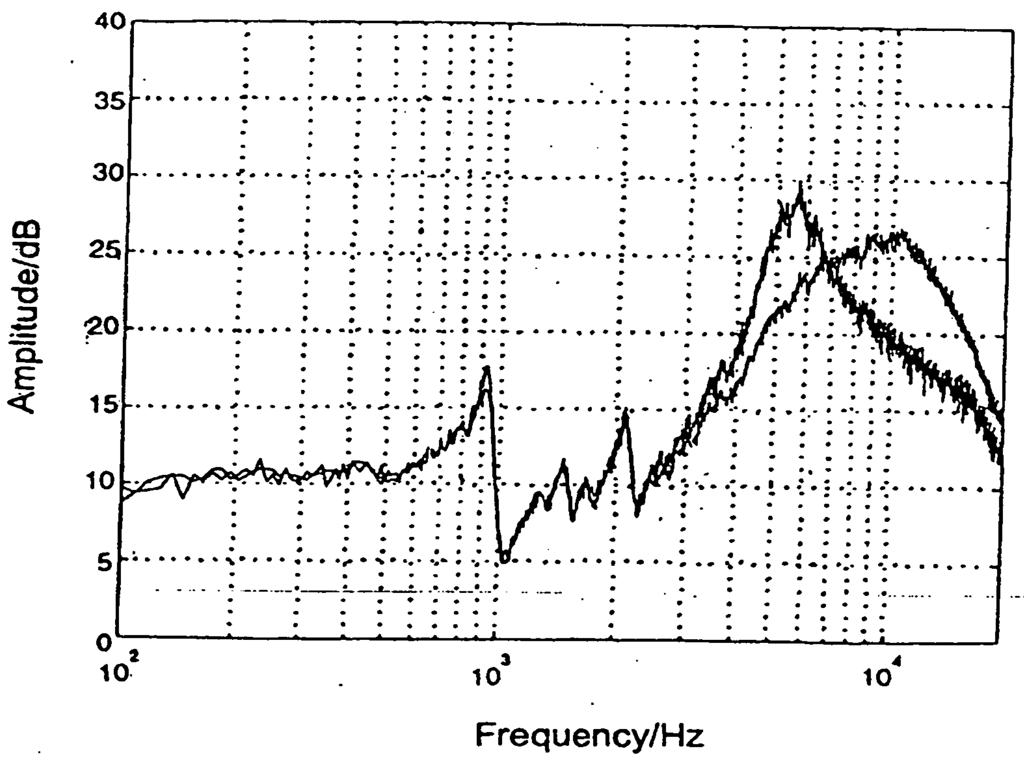

Fig. 5

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